Title: Increasing the Dose Rate on the DARHT-II Accelerator

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Introduction

Recent studies [1] have shown a strong correlation between spot size on target and the dose. At higher doses, the spot size is larger. At very low doses (< 75 R @ 1m per pulse) all four spots are small and essentially the same with 50%MTFs of 1.0-1.2 mm. For higher dose pulse formats, the first two pulses, P1 and P2 remain small (< 1.2 mm 50%MTF) and relatively independent of dose. The later pulses, P3 and P4, become larger as the dose increases. Longer pulse lengths are required to achieve higher doses. There are simulations that suggest space charge neutralization [2] and current neutralization [3] could be introducing dynamic changes in the spot size over the pulse. This implies that increasing the dose rate will allow for reduced pulse lengths and spot size for the same dose.

Equation (1) shows the major factors that contribute to the dose and dose rate are beam energy, E, beam current, I, and pulse length Δt. Shorter pulse lengths producing the same total dose requires increasing the energy and/or current with the same fractional increase in energy compared to current being a factor of about three higher.

$$Dose \ \approx I\, \Delta t\, E^3 \ \Rightarrow \ \text{Dose Rate} \approx IE^3 \tag{1}$$

There is also evidence that increasing the current may exacerbate these dynamic processes that increase spot size. On the basis of this argument, methods to increase the beam energy in particular and to a lesser extent the beam current of the DARHT-II linear induction accelerator will be investigated.

Discussion

DARHT-II has been operated in three configurations since completion of the refurbishment project in 2008. The three configurations represent three different operating voltages of the Marx injector and two nominal settings of the accelerator cell voltages. These configurations are:
1. 2008 (18 MeV and 2.05 kA actually 17.2 MeV with four cells off)
    a. 38 kV Marx charge voltage
    b. 250 kV unloaded accelerator cell voltage
2. 2009-2011 (16.5 MeV and 1.84 kA)
    a. 34.5 kV Marx Charge voltage
    b. 225 unloaded accelerator cell voltage
3. 2011-present (16.5 MeV and 1.65 kA)
    a. 31 kV Marx Charge voltage
    b. 225 unloaded accelerator cell voltage

The change from configuration 1 to configuration 2 was made to improve reliability. The Marx charge voltage and the unloaded cell voltages were reduced by 10%. The change from configuration 2 to configuration 3 resulted from loss of injector voltage conditioning after prolonged exposure to atmosphere. Injector reliability at Marx charge voltages above 31 kV was poor. The analysis in Appendix

A was performed at this time showing the total beam energy would not change and the 11.5% reduction in current had to be compensated by longer kicker pulses to maintain dose. It is highly likely that in the last ten years the conditioning of the Marx has improved and it should be possible to return to the previous Marx charge voltage of 34.5 kV.

Comparing IE^3 for the three cases yields 11956, 8265 and 7412 kAMeV^3 respectively for Cases 1, 2 and 3. The ratios of the prior operating conditions to today are 1.61 and 1.12 for cases 1 and 2 respectively. The difference between cases 2 and 3 is due to the increased beam current because the increased injector energy is almost exactly compensated for by increased cell loading as described in the Appendix A. The unloaded cell voltages for case 1 and case 3 are shown in Figure 1. The average accelerator cell voltage (cells 9-74) is about 26 kV higher for case 1. This alone could increase the energy by 1.72 MeV and the dose by about 30%.
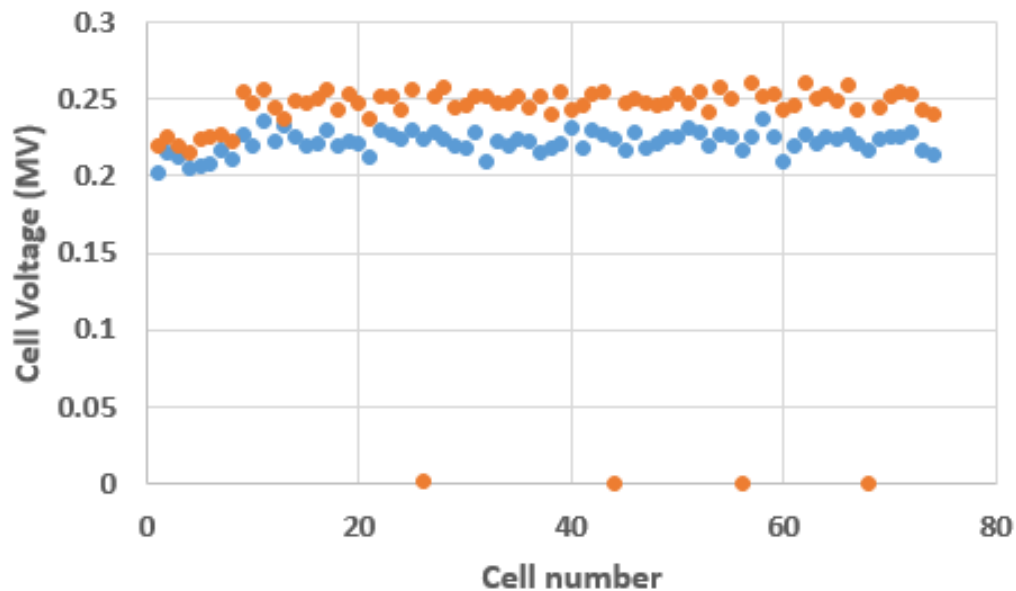

Figure 1: Unloaded cell voltages for shots 8387 (July 2008) in orange and 38171 (July 2021) in blue. The voltage is measured at a time of 2.7 us.

The decision to reduce the cell voltage by 10% was somewhat arbitrary since all cells had been tested and operated at voltages higher than 250 kV prior to installation. The reliability of the cells did improved significantly as only one cell has partially failed since 2009. This cell has worked well at a lower voltage without incident since.

A 10 kV reduction in the cell voltage of case 1 is proposed. This has the potential to increase the beam energy from 16.38 to 17.63 MeV as measured at 2.7 us taking into account the beam loading associated with 1.65 kA. This projects to be a 25% increase in dose rate.

Further increases in dose rate could be realized by increasing the Marx voltage which would represent an increase in the beam current. Returning to the Marx charge voltage of 34.5 kV would increase the current from 1650 to 1850 A with an additional 12% increase in dose rate. Both of these improvements would produce a 40% increase in dose rate.

Summary

      This note examines a path forward to increase the dose rate on DARHT-II. The improvement in spot size that can be realized with shorter kicker requires experimental data because the nature of the interaction that causes larger spot sizes for P3 and P4 in high dose pulse formats is not completely understood. These experiments should lead to a better understanding of the beam target interaction. Independently increasing the energy and current should also be examined.

      Prior to tuning the accelerator to operate at higher energy and/or current, it will be necessary to demonstrate operation of the Marx injector and accelerator cells at higher voltages. The accelerator cells can be tested and conditioned beginning with very small (1-2 kV) increases in charge voltage. A new accelerator tune will be required once the operating parameters are determined.

References

[1] M.E. Schulze, "Contributions to Target Spot Size in Single and Multi-pulse Radiography", LA-CP-21-20235, March 2021.

[2] M.E. Schulze, "A Simulation of the Ion Focusing at the DARHT-II Target", LA-CP-18-20064, February 2018.

[3] M Jaworski, private communication.

APPENDIX A: Beam Current, Energy and Loading on DARHT-II

The final beam energy of the DARHT-II accelerator is relatively insensitive to the Marx charge voltage. This is due to beam loading in the accelerator cells whereby higher current beams receive less acceleration in the cells. The accelerator cells are operated at the identical unloaded voltage for all cases.

Simplistic description of beam loading:

The voltage gain in each accelerator cell is determined by the unloaded cell voltage less the beam loading term. The beam loading is about 15 keV/kA. This means that a 2000 A beam in a 250 kV cell will only see an energy increase of 220 kV. An 1800 A beam will see an energy increase of 223 kV.

Results:

Figure A1 shows the measured beam current as a function of Marx charge voltage. There is clearly more current as the charge voltage is increased. The current increase about 170 A as the Marx charge voltage is increased from 33 to 36 kV. This is consistent with the current being a function of the voltage to the 3/2 power ($I = kV^{3/2}$).   Figure A2 shows the A-K voltage as a function of time for different values of the Marx charge voltage. As the charge voltage is raised from 33 to 36 kV the injection energy increases from 2.2 to 2.4 MV. Figure A3 shows the beam energy at the accelerator exit. Note that the effect of more beam loading at higher current completely cancels the increased injection energy so that the beam energy at flattop is essentially independent of the Marx charge voltage. The only effect of

operating a different Marx charge voltage is the increased current realized at higher Marx charge voltages.
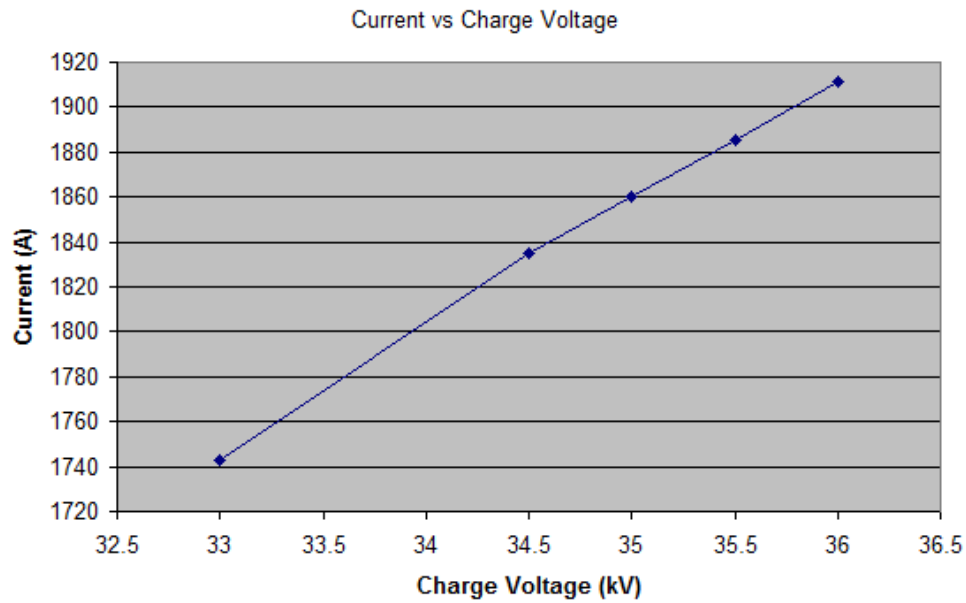

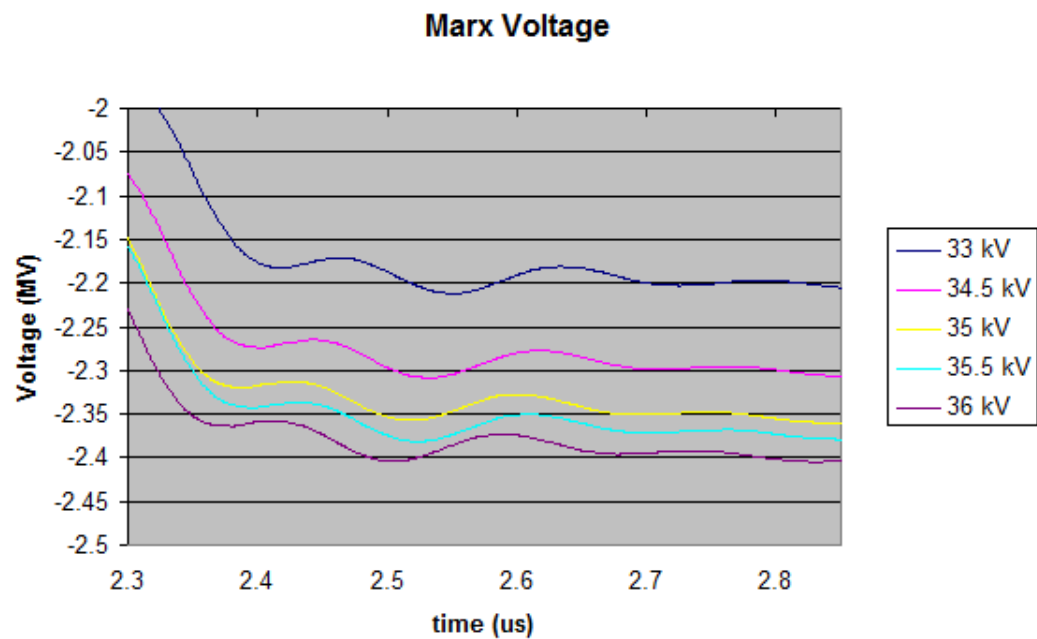Figure A1: Beam current as a function of Marx charge voltage

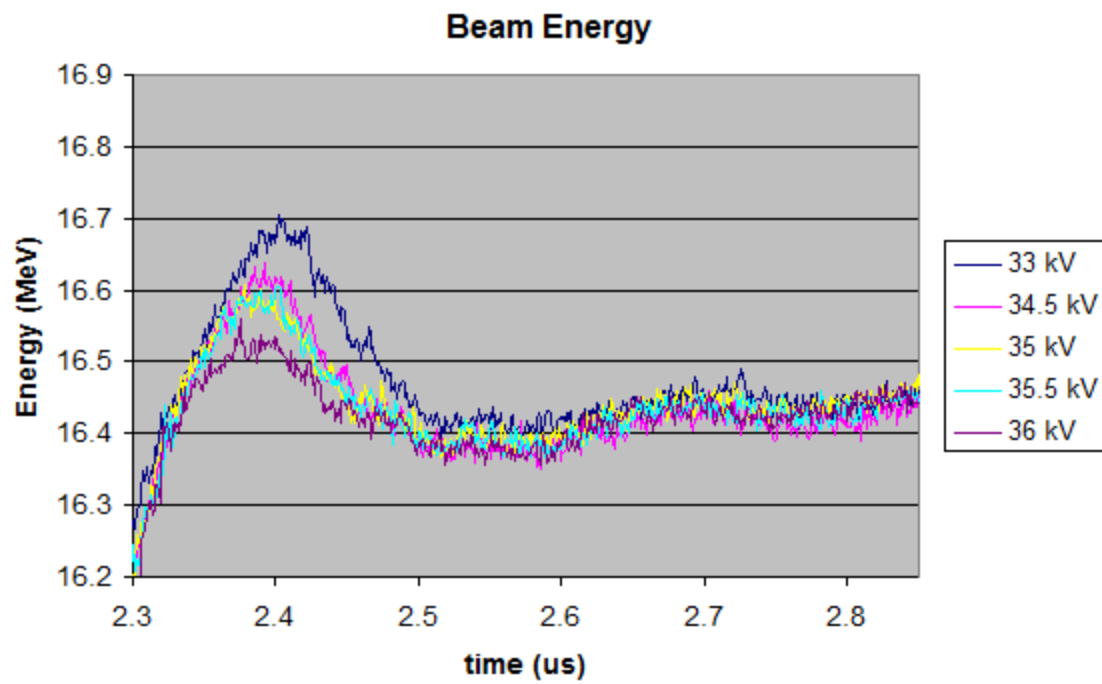Figure 2: AK voltage as a function of time for different Marx charge voltages

Figure A3: Beam energy as a function of time for different Marx charge voltages